# A Model of the Cognitive and Perceptual Processes in Graphical Display Comprehension

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## Abstract

Graphs are used extensively to facilitate the communication and comprehension of quantitative information, perhaps because they seem to exploit natural properties of our visual system such as the ability to process large amounts of information in parallel. Rather than a holistic pattern recognition process, however, research has found that graph comprehension is a complex, interactive process akin to text comprehension. Viewers form a mental model of the quantitative information displayed in the graph through serial, iterative cycles of identifying and relating the graphic patterns to associated variables. Furthermore, graph comprehension is not only constrained by bottom-up perceptual features of the graphical display, but is also influenced by top-down factors such as the viewer's expectations about, or familiarity with, the graph's content. Finally, individual differences in graph comprehension skill interact with top-down and bottom-up influences such that highly skilled graph viewers are less influenced by both the bottom up visual characteristics, and the top-down semantic content.

## Introduction

Graphical displays are one of the primary means for the representation, communication, and dissemination of quantitative information. Graphs are used to depict mathematical functions, display data from social and natural sciences, and specify scientific theories. As a result, graphical displays are used extensively in textbooks, scientific journals, and the popular media.

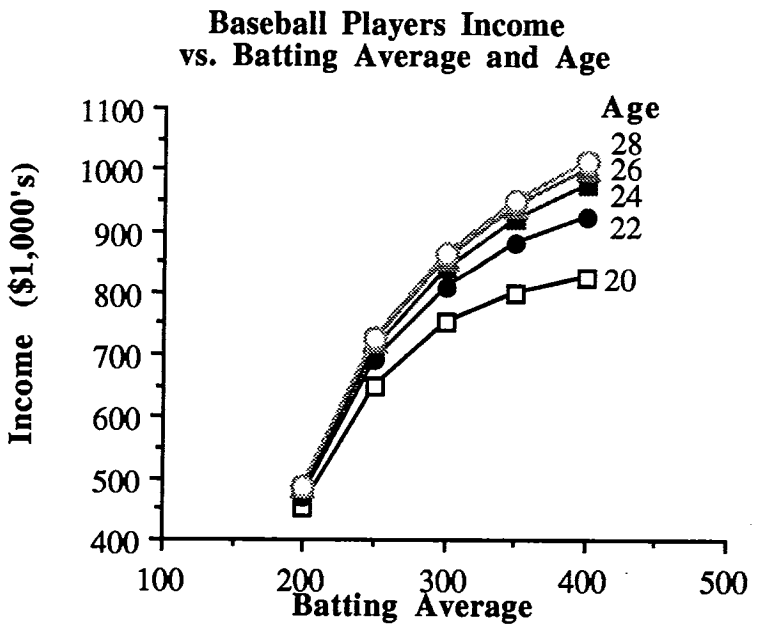
What are the processes by which viewers interpret graphs? What makes some graphs easy to understand for some people, and what makes other graphs difficult to understand? The goal of this paper is to outline a cognitive model of graph interpretation, based on a series of empirical studies. An understanding of how viewers interpret graphs, and the factors that make them easy and difficult for different populations, may help us to solve many practical, as well as theoretical problems. The practical problems include how graphs might be created by graphic designers, scientists, and automatic data display systems to more effectively communicate quantitative information (Shah, Mayer, & Hegarty, 1997).

## The Model

A model of graph comprehension will share some characteristics of more general models of diagram interpretation. However, graphs are unique compared to other diagrams and visual displays. They are based on *rational imagery*, meaning that information that is presented is systematically related to the graphic representation (Bertin, 1983). The relation is neither arbitrary, as is the relation between words and concepts, nor a first-order isomorphism, as is the relation between pictures and their referents (Winn, 1987). Graphs can be distinguished from partially abstract diagrams that are meant to depict visuo-spatial information (for example, mechanical diagrams of pulley systems or biological diagrams of the functioning of the circulatory system) because graphs represent some *quantitative* property of either concrete objects or abstract concepts. The relation between a represented concept and the graph is based on an analogy between quantitative scales and visual dimensions such as length, color, or area in which the visual dimensions are usually analog representations of this quantitative information (Bertin, 1983; Hegarty, Carpenter, & Just, 1991; Pinker, 1990). Thus, in the continuum of different forms of written information, graphs are more abstract than pictorial diagrams, but still represent information in an analog, non-arbitrary fashion.

Researchers have suggested that it is this "rational", or "natural" link between quantitative and spatial information that makes graphs particularly well-suited for representing quantitative information (MacDonald-Ross, 1977; Pinker, 1990; Winn, 1987). Indeed, graph comprehension can seem easy, particularly when a trend or quantitative relationship is explicitly represented in the visual features of the graph (Larkin & Simon, 1987) or when a viewer has already learned the association between a graphic feature and a quantitative relationship, such as "an upwardly curved line indicates an accelerating relationship" (Pinker, 1990). In the graph in Figure 1, for example, the reader will easily detect the decelerating relationship between batting average and baseball player's income. In order to understand the same relationship in the table below, by contrast, a viewer must effortfully compute the relative differences in the numbers in the cells.

However, both task analyses of graph comprehension (Bertin, 1983; Pinker, 1990), as well as errors viewers




**Baseball Player's income (in $1,000's) vs. Batting average and Age**

Batting Average

| Age | 200 | 250 | 300 | 350 | 400 |
|---|---|---|---|---|---|
| 20 | 450 | 650 | 750 | 800 | 825 |
| 22 | 470 | 690 | 810 | 880 | 925 |
| 24 | 480 | 710 | 840 | 920 | 975 |
| 26 | 485 | 720 | 855 | 940 | 1000 |
| 28 | 487.5 | 725 | 862.5 | 950 | 1012.5 |

*Figure 1.* A graph and table depicting the same data. In the graph above the decelerating, increasing relationship between batting average and income is explicitly plotted in the x-y lines. In the table below, the deceleration is inferred by the decreasing differences between the numbers in the table.

make in graph comprehension (Culbertson & Powers, 1959; Shah & Carpenter, 1995; Shah, Mayer, & Hegarty, 1997; Vernon, 1950), suggest that a complex set of cognitive processes underlies the apparently effortless comprehension of graphs (Guthrie, Weber, & Kimmerly, 1993). In addition, viewers' internal representations of data are often inaccurate or incomplete. This is true of not only college students, but also of populations with significant experience in data analysis and interpretation (Shah & Carpenter, 1995). Consider, for example, the graph in Figure 1 once again. Although the graph explicitly depicts the increasing, decelerating, relationship between batting average and income that most experienced graph viewers readily comprehend, the graph also depicts a similar relationship between age and income that is much more difficult to comprehend.

A fundamental issue in graph research, then, is the characterization of the interpretation processes and the principled identification of the characteristics of graphic formats, data sets, and interpretation tasks, that influence the interpretation processes. In this paper, I review a number of studies in which I and others examine how task and graph characteristics lead to different internal representations of data, representations that support relatively effortless and automatic retrieval of some quantitative concepts, and the effortful and complex induction of other quantitative concepts.

These studies show that the interpretation of many commonly used graphs is the result of a complex sequence of cognitive processes, processes that are highly limited and systematically biased. The time it takes to form a even simple interpretation of some graphs in our studies can be about 30 seconds, or the same amount of time as reading

and understanding a paragraph of text, rather than the time to say, recognize an object. Indeed, this research suggests that the interpretation of graphs, shares many of the characteristics of text comprehension.

Specifically,

1) Graph comprehension involves

a) Bottom-up processes in which people extract visual chunks that explicitly represent a limited number of quantitative facts or relations. Information that is not explicitly represented in those visual chunks must be computed by inferential processes that are difficult and error prone.

b) Top-down processes in which knowledge of semantic content also influences viewers' interpretations of data.

2) The interaction of top down and bottom up processes is individually applied to different chunks, so that the interpretation process is serial and incremental, rather than automatic and holistic.

3) Individual differences in graph comprehension skill interact with top-down and bottom-up influences such that highly skilled graph viewers are less influenced by both the bottom up visual characteristics, and the top-down semantic content.

In the next section, I describe some of the empirical evidence supporting each of these conclusions.

## Empirical Support for the model

### Bottom-Up Processes

As discussed above, one of the oft-touted advantages of graphical displays is the fact that they "take advantage of the visual perceptual processing system." This general statement has been made in reference to a wide variety of graph comprehension tasks and graphical displays, from scientific discovery (Gleick, 1987; Lewandowsky & Spence, 1989) to exploratory data analysis (Tukey, 1977; Wainer & Thissen, 1981). The assumption is that graphical displays, because they depict quantitative information visually, make explicit certain quantitative facts and relations that may not have been previously apparent or obvious from other media such as text or tables. For example, chaotic patterns of weather were discovered when multiple time-series plots were placed on top of one another (Gleick, 1987). The similarities and slight differences between the visual patterns suddenly "popped out," demonstrating the potential power of the perceptual aspect of graph comprehension.

Thus, according to the previous theoretical and computational approaches to graphical display comprehension (e.g. Casner, 1990; Casner & Larkin, 1989; Larkin & Simon, 1987; Lohse, 1993; Pinker, 1990), graphical displays are most useful when they make quantitative information perceptually obvious so that it can be retrieved "automatically", minimizing cognitive effort and maximizing the perceptual advantage of graphs over other ways of presenting quantitative information (Larkin & Simon, 1987; Pinker, 1990). By implication, the visual characteristics of the graphical display, then, should have an influence on what kinds of information are easy and difficult to comprehend from a graph.

Much previous research that has compared the speed and accuracy of identifying different quantitative facts and relations from different graphic formats has supported this view (e.g. Cleveland & McGill, 1984, 1985; Legge, Gu, & Luebker, 1989; Spence, 1990). For example, Carswell & Wickens (1988) found that bar graphs and other "separable" displays were better suited for identification of individual facts. By contrast, line graphs, and other displays that integrated two or more variables, were better suited for tasks that required synthesis.

In recent research, my colleagues and I have examined how the characteristics of graphical displays influence not just the speed and accuracy of making perceptual judgments, but viewers' ability to describe, interpret, and explain quantitative relations. In these studies, we have begun to specify, for different graphic formats, exactly what visual features are "mapped" more or less automatically to quantitative conclusions, and what information is more difficult to retrieve and must be inferred by complex processes. We examined expert and novice viewers' interpretations of a number of commonly used graphic formats: line graphs, bar graphs, divided bar charts, and "three-dimensional" wireframes. For each of these formats, we have found that viewers are able to retrieve a limited number of quantitative facts or relations that are highly constrained by the kinds of visual chunks made explicit by the display. When information is not explicitly represented in a particular graphic format, viewers have tremendous difficulty understanding that information and are often unable to do so. Below, I describe a few of the studies in which we specify the way in which the graphic format influences viewers interpretations of data.

**Line Graphs.** In one series of studies, we examined the interpretation of line graphs, specifically, the limitations that influence a viewer's comprehension of these line graphs (Shah & Carpenter, 1995). In these studies, viewers were asked to briefly describe or explain a series of individually presented three-variable line graphs, such as the graphs in Figures 1 and 2. The viewers' descriptions and/or explanations were coded according to the type and amount of information they included about the relations presented in the graphs.

Overall, the results suggested that the comprehension of line graphs involves abstracting a limited set of propositions that describe the functional relations depicted by the x-y lines of the graphs; viewers rarely described

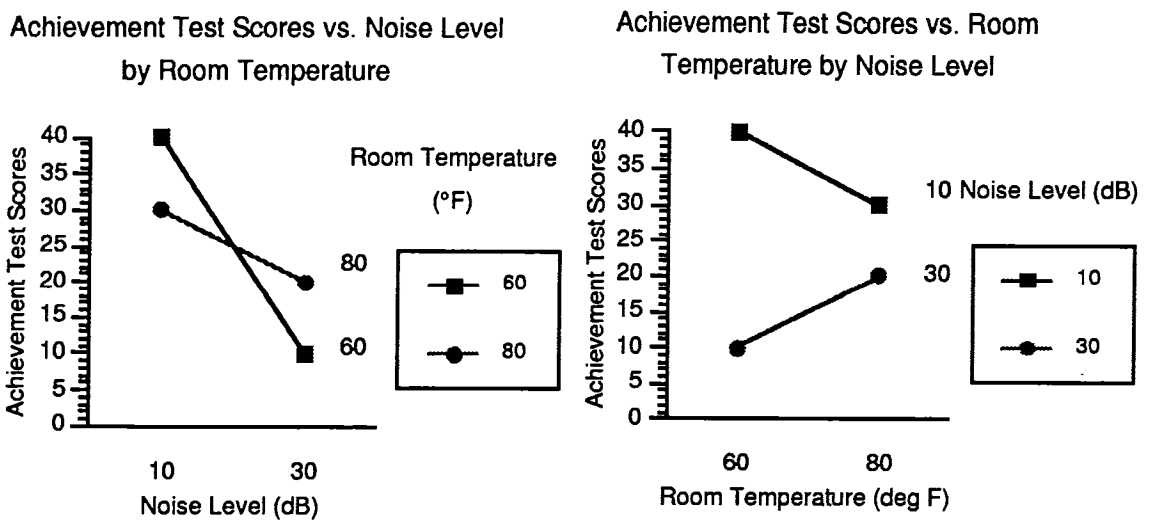



*Figure 2.* Two perspectives the same data set in which the main visual features of the graphs differ greatly, leading to qualitatively different interpretations of data.

more than nominal or ordinal information about the parameter on the curve (in Figure 2a, the relationship between room temperature and achievement test scores). A typical description of the graph in Figure 2a, for example, is that

a) Achievement test scores decrease as noise level increases when it is 60 degrees;
b) Achievement test scores decrease as noise level increases when it is 80 degrees;
c) Achievement test scores decrease more when it is 60 degrees than when it is 80 degrees.

But the graph in Figure 2b elicits qualitatively different verbal description focusing on its x-y lines

a) Achievement test scores decrease with room temperature for low (10 dB) noise levels;
b) Achievement test scores increase with room temperature for high (30 dB) noise levels;
c) Achievement test scores for low (10 dB) noise levels are higher than for high (30 dB) noise levels.

Viewers not only described graphs differently depending on what information was coded on the x-axis, but were often unable to recognize the same data (on 32% of trials viewers judged the same data to be different) or draw the alternative perspective. These studies suggest that for line graphs, the major visual chunks are the x-y lines. When information is not explicitly presented in the lines on the graphs viewers, even experts, often have difficulty interpreting data.

**Line Graphs vs. Bar Graphs.** In another series of studies, we examined how the format of a graphical display (line graph or bar graph), as well as the scale of the graph (absolute vs. percent), influenced viewers' interpretations of data (Shah, Mayer, & Hegarty, 1997). Overall, we found that viewers were much more likely to be able to describe and answer questions about information that is explicitly represented in graphs. When graphs require any kind of mental computation, such as integrating information across a display or translating from an absolute to percent scale, viewers have tremendous difficulty and were often unable to do so. More specifically, these studies characterized the kinds of visual chunks that are retrieved for line graphs and bar graphs. As in the previous studies, we found that line graphs emphasize x-y trends. By contrast, bar graphs emphasize comparisons that are closer together on the display. Finally, we found that line graphs are more biasing (emphasizing the x-y relations), while bar graphs are more neutral.

**Line Graphs vs. Wireframes.** A third series of studies examined the kinds of interpretations viewers gave to line graphs and three-dimensional wireframe graphs such as the graph in Figure 3. These studies demonstrate that the internal representation of line graphs and wireframe graphs emphasize different properties of the data. A typical description of a line graph includes descriptions of the x-y lines, including differences between lines and changes along the x-axis. Viewers provide more varied descriptions of wireframe graphs, often describing maxima, minima, and/or shape of the data space in addition to some information about the quantitative relations. Thus, wireframe graphs, particularly the landscape-like complex graphs in this study, lead to qualitatively different interpretations that emphasize configural properties rather than quantitative relations.

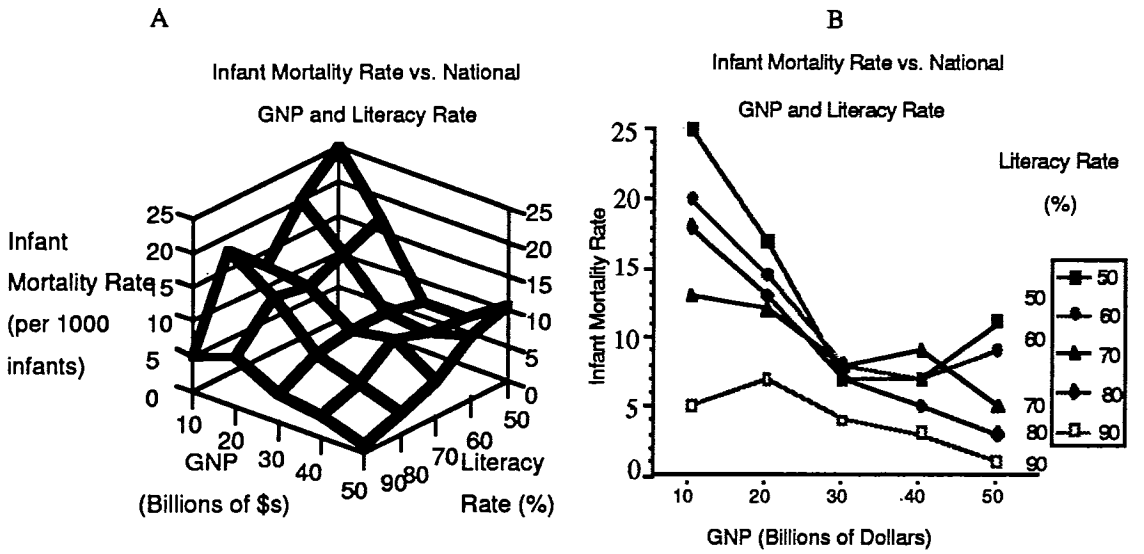



*Figure 3.* The wireframe graph in Figure 3a supports a spatial representation of data in which the important graphical features, such as maxima and minima, are represented. By contrast, the line graph in Figure 3b supports a propositional representation that emphasizes a decreasing relationship between year and mortality rate.

**Summary.** A number of studies demonstrate that the perceptual characteristics of the visual display, in particular the kinds of visual chunks that are retrieved in comprehending different graphic formats, influence viewers interpretations of data. Thus, just as characteristics of text, such as coherence (van Dijk & Kintsch, 1983), influence what kinds of inferences readers can easily make, the characteristics of the graphical display influence what kinds of quantitative inferences graph viewers can make. In designing graphical displays, as in designing text (Bereiter & Scardamalia, 1982), it is not merely enough that information is presented technically correct, but also that it is designed to effectively communicate the relevant quantitative information.

## Top-Down Processes

A second major characteristic of our model of graph comprehension is that, in addition to a bottom up influence of the characteristics of the graphical display, there is a top-down influence on the semantic content of the quantitative information that is depicted in the graph. Again, this aspect of a model of graph interpretation has parallels to models of text comprehension. Specifically, models of text processing incorporate the notion that readers' prior knowledge, expectations, and goals influence the process by which they read and the kinds of information that they comprehend and remember about a passage (*e.g.*, Kintsch & van Dijk, 1978; van Dijk & Kintsch, 1983).

In the general case, it appears that viewers encode and remember pictures and diagrams differently depending on their knowledge and expectations. For example, verbal labels have long been known to distort viewers' memory for ambiguous pictures (Carmichael, Hogan, & Walter). More recent evidence suggests that viewers have schemas for graphs and maps that distort their representations of them. For example, participants in one study who were asked to draw line "graphs" from memory tended to distort the lines and draw them as being closer to 45∞ than the lines originally were (Schiano & Tversky, 1992; Tversky & Schiano, 1989). When they were told that the same display depicted a map, however, they distorted the lines so that they were closer to 0∞ or 90∞.

What about the viewers expectations about the semantic content of graphical displays? Much research in graph comprehension has examined graph interpretation in abstract or arbitrary domains, but comparatively little research has examined how the semantic content of the variables influences the interpretation of graphs (Carswell, Emery, Lonon, 1993; Leinhardt *et al*, 1990). In recent research, I have begun to examine how the semantic content of graphs influences the kinds of interpretations viewers give to data . In these studies, I examined the role of familiarity with the quantitative relations presented in graphs as well a viewers' causal expectations.

**Familiarity.** The premise of the first study was that viewers would be more likely to interpret relationships between variables for which viewers had expectations about general trends, such as number of car accidents, number of

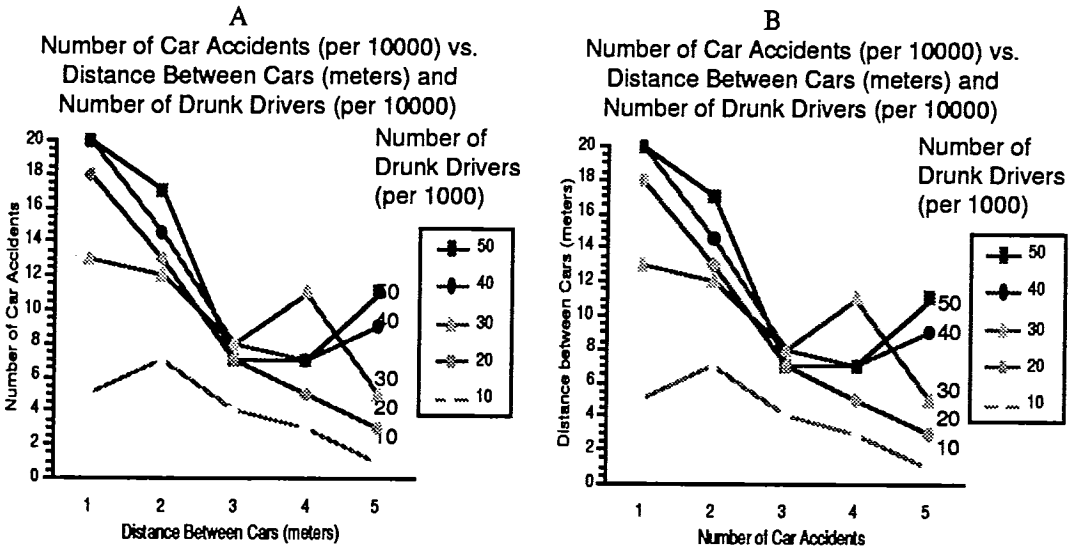



*Figure 4.* Figure 4a (left) shows a conventionally plotted graph that is consistent with most viewers' expectations of the causal relations between these variables. In figure 4b (right), the x- and y-axes are reversed.

drunk drivers, and traffic density, compared to variables for which viewers did not have any expectations, such as ice cream sales, fat content, and sugar content (Shah, 1995). The results from this study suggest that when viewers had particular expectations, they were likely to describe those relationships (for example, as drunk driving increases, car accidents increase), ignoring "idiosyncratic" data points such as local maxima and minima that were inconsistent with the general expected trends. By contrast, when viewers did not has expectations, they were less likely to describe general trends, and more likely to describe local maxima and minima. These results suggest that viewers' familiarity with quantitative trends influenced whether or not they would describe those trends.

**Expectations about Causal Relations.** In a second experiment, I examined viewers expectations of causal relations that are depicted in graphs (Shah, 1995). The assumption was that, given a set of familiar variables, viewers are likely to have some expectations about the directionality of causal relations. For example, one expectation is that increased rates of drunk driving or decreased distance between cars cause car accidents and not vice versa. In this study, viewers were presented with graphs that depicted data about common topics, in which the likely dependent variable (the number of car accidents) was plotted on the y-axis (*conventional*) as shown in Figure 4a, or on the x-axis (*reversed*), as shown in Figure 4b.

When the position of graphic variables is conventional, viewers were able to use their knowledge about the graphic format and the variables to make accurate inferences about the quantitative relations. However, when graphs are plotted so that the data are inconsistent with viewers expectations about causal relations, viewers frequently described relations that were not actually depicted in a graph but are consistent with their expectations or models about the causal relations. For example, even though the graph in Figure 4b does not depict a relationship between the number of drunk drivers and the number of car accidents, most viewers would expect a relationship between those two variables, and novice graph viewers inaccurately described this relationship on 93% of the trials.

## The Serial Nature of Graph Interpretation

Models of graph interpretation that are based on task analyses tend to emphasize the holistic, pattern recognition aspects of graph interpretation (as reviewed by Guthrie et al, 1993). According to these models, most of the "cognitive" action in interpreting graphs occurs in encoding the visual features of the graphical display and relating them to their quantitative conclusions (Pinker, 1990). By contrast, other aspects of the interpretation process, such as relating the meaning of the graph to the quantitative relations, are given much less importance.

However, a series of studies in which we examined viewers eye fixations as they answered questions about line graphs (Carpenter & Shah, 1997) supports our claim that the interpretation of graphs is serial and incremental. Viewers identify individual quantitative facts and relations,

based on the component visual chunks of a display, and relate them to their graphic referents.

**Eye fixation studies.** To study the process of graph comprehension, we examined the pattern and duration viewers' gazes on line graphs (like the ones shown in Figures 1 and 2) as they described and answered questions about graphs. The results demonstrated that the comprehension of graphs is complex, with viewers spending the majority of the time interpreting a graph relating information from the lines on the graph to their referents, rather than viewing the patterns of lines themselves. Furthermore, the results supported a model of graph interpretation in which viewers serially identify each individual visual chunk and relate it to its graphic referents (the variable names). This iterative model can predict the distribution of viewers' gazes across different parts of a graph as well as the total number of gazes required to interpret graphs that vary in complexity.

### Individual Differences

The final characteristic of our model of graph interpretation is that individual differences in graph interpretation skill interact with the bottom up influence of the graphic format and the top down influence of the semantic content (Shah, 1995). Current studies are continuing to investigate the role of individual differences in graph interpretation, but data from our previous studies provide preliminary support for the conclusion that expertise in graph interpretation mitigates the effects of the both the visual characteristics of the graphical display, as well as the semantic content.

For example, in the study of the interpretations that viewers gave to line graphs and wireframe graphs, viewers provided qualitatively different interpretations of the data. A closer examination, suggests, however, that there were two different groups of subjects. One group was responsible for the differences in the two graphic formats. The other group, which had higher mathematics SAT scores, and their likely correlated experience and expertise in using graphs, gave similar descriptions of the two formats. These results correspond to other kinds of aptitude treatment interactions, in which the way in which information is presented matters more for less skilled readers or viewers.

Similarly, our studies suggest that individual differences in graph interpretation skill also influences the effect of the semantic content of the graph. Novices described graphs that depicted reversed causal models inaccurately 93% of the time, describing what they expected rather than what the graph said. By contrast, experts rarely made this errors (17%).

Thus, the current studies suggest that graph interpretation skill may play a role in how well viewers can accurately interpret a graphical display, even when a graph is not plotted to explicitly represent that information, or the viewer has prior expectations that differ from the information presented in the graph.

## Conclusions

In summary, cognitive research supports a model of graph comprehension in which interpreting a graph involves translating the visual features of a graph to a conceptual representation of the quantitative information via multiple, integrated cycles of identifying quantitative relations and the variables associated with them. The model assumes that graph viewers have knowledge about different graphic formats that influences and supports the interpretation process. The relative ease or difficulty in interpreting graph occurs because two kinds of processes are involved in comprehending different kinds of information from a graph. If the graph supports visual chunks that the viewer can mapped to relevant quantitative information, then it may be automatically retrieved. If not, quantitative information must be computed by inferential processes that consist of a number of retrieval and comparison substeps. When graph viewers have less experience interpreting graphs, they may be forced to rely on semantic knowledge even if this knowledge is not consistent with the data. Thus, the model proposes that viewers' knowledge about graphic formats, and expectations about the relationships between particular variables, have a top-down influence on the kinds of interpretations that viewers give to graphs.

This model had a number of theoretical and practical implications. Theoretically, this research suggests that a computational model of graph interpretation will need to incorporate the following features:

1) The ability to support the automatic retrieval of some quantitative facts (if straight line, linear relationship)

2) Individual identification of each quantitative function or fact.

3) Individual differences in knowledge influence about what visual features imply.

4) The ability to identify and compare values to infer relations.

5) Limited capacity in the amount of information viewers can maintain.

6) Interactivity: perceptual properties influence interpretation, knowledge about graphs and quantitative relations influence what viewers encode.

There are also a number of practical implications of graphic design relevant for both people (Shah, Mayer, & Hegarty, 1997) and automatic data display systems (Roth & Hefley, 1993). Different ways of presenting data can influence what is easy to retrieve and therefore what viewers are likely to encode. In designing graphical displays one should use knowledge of the bottom-up influence of graphic format to design displays that

maximize retrieval and minimize difficult inferential processes. In addition, because viewers are able to comprehend a limited amount of information, an individual graph should contain at most a couple of relevant quantitative concepts. Finally, graphic design should be catered to the audience; it is particularly important to pay attention to the characteristics of graphical displays for novice graph viewers.

## Acknowledgments

This research was supported by a James S. McDonnell Postdoctoral Fellowship for Cognitive Studies in Educational Practice. I would like to thank Mary Hegarty and James Hoeffner for comments on this paper.

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